# State Advisory Board on Air Pollution

# Subcommittee on Ammonia Inventory Methodology

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## For Presentation to the State Air Pollution Control Board

## Richmond, Virginia

## November 7, 2001

# 10/7/01 SAB-AP Subcommittee Report on Ammonia Inventory Methodology

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## Executive Summary

The mission of this Subcommittee on Ammonia ($NH_3$) Inventory Methodology, under the State Advisory Board on Air Pollution (SAB-AP), is to advise the Virginia SAPCB and DEQ on the potential need (if any), and methodology required, for calculating an inventory of airborne ammonia emissions for Virginia.

This research project stemmed from the framing of a question:  Will the effects of future increases in excess ammonia emissions ("$NH_3$ slip"), from anticipated installations of Selective Catalytic Reduction (SCR) or Selective Non-Catalytic Reduction (SNCR) flue gas processors (air emission control technologies that use $NH_3$ to reduce $NO_x$ to $N_2$ and $H_2O$ emissions), be significant and require regulatory action by the DEQ and SAPCB?

Clearly the development and maintenance of an ammonia inventory listing would provide basic data for the DEQ and others to assess incremental effects of increased industrial ammonia emissions on regional haze, neutralization of rain acidity, incidental soil alteration/fertilization, and eutrophication of the Chesapeake Bay.  However, detailed implementation of such a program would also require substantial DEQ resources.  Thus the "cost/benefit" ratio becomes a consideration.  Furthermore, the actual need for conducting a detailed inventory appears minimal, based on presently available information described below.

Fortunately, the essential detailed information on developing an ammonia inventory is available as an EPA-sponsored study entitled "*Development and Selection of Ammonia Emission Factors*" by Battye *et al.* (August 1994).  Our analyses of relevant data indicate animal wastes and soil fertilization now account for about 60% of present ammonia air emissions in Virginia.

Detailed assessments of ammonia ($NH_3$) slip emission concentrations and quantities, for projected installations of SCR's and SNCR's in Virginia, were beyond the scope of this study; however, a provisional regional assessment was developed.  Projected $NH_3$ slip quantities, based on planned SCR and SNCR installations in Virginia (Dominion Generation, for CY's 2004-2007), were made corresponding to targeted $NO_x$ reductions during "the 5-month ozone season."

Resultant projected total $NH_3$ slip quantities for a 5-month season were relatively small (from 12.8% to 4.4%), compared to estimated total annual $NH_3$ air emissions in Virginia from animal waste, fertilization, soil, TRI and SCR/SNCR sources, refrigeration, mobile sources (which have grown considerably with recent catalytic mufflers), and Publicly Owned Treatment Works.

The first estimate (12.8%) corresponds to DG's projection of 85% SCR and 15% SNCR process contributions.  It used average $NH_3$ slip efficiencies recommended by Battye *et al.*, based on extensive but highly variable data obtained a decade ago.  The lower impact estimate of 4.4% applies *if* highly efficient and well-maintained SCR processes are utilized for nearly all $NO_x$ reduction, so that utilization of much less efficient SNCR processes is effectively eliminated.

Thus our analyses suggest that (preferable) SCR process installations would not become significant regional contributors of $NH_3$ air emissions.  Important operational factors that favor relatively low local and regional impacts are:  $NH_3$ is moderately expensive, so that operating

costs of $NH_3$ wastage weigh significantly against the costs of proper catalyst bed maintenance; $NH_3$ slip concentrations from modern SCR's, which may be subject to regulation, are expected to be relatively low (say, 5 ppm, on average); and finally, total $NH_3$ amounts (consumed plus slip) are essentially linked to target $NO_x$ sources being "reduced," which have well defined bounds.

It is concluded, based on the Battye *et al.* studies[4,5] and the present assessment, that (1) efforts to develop and maintain a detailed ammonia inventory appear unnecessary, and (2) incremental regional (and local) effects of expected additional $NH_3$ slip emissions, from the (assumed) predominance of SCR applications, should be relatively small for the next decade.

## Why an Ammonia Inventory? -- Regional Haze, Acid Rain, Eutrophication

Ammonia contributes to both the growth of regional haze particles, and neutralization of their acidity. These (typically) aqueous aerosols stem from long range transport of acidic sulfates and nitrates, largely from power plants in the Ohio Valley area, and increasingly from the cumulative effect of distributed (e.g. mobile) $NO_x$ sources. Regional haze is an environmental and regulatory issue impacting Virginia, and of special concern to the Shenandoah Valley.

One of the goals of the Clean Air Act is to restore National Parks (known as Class I areas) to 'natural background' conditions. EPA responded to this goal by promulgating a final Regional Haze Rule on July 1, 1999 (64 Fed. Reg. 35,713-74). This rule requires restoration of Class I areas to natural background conditions by 2064. Federal land managers are thus developing limits of acceptable change for each Class I area.[1]

Achieving the goals of the Regional Haze Rule will be primarily the responsibility of the States. State Implementation Plans (SIPs) are the means for accomplishing this, with Best Available Retrofit Technology (BART) controls for certain existing sources, including power plants and other industrial facilities that began operation on or between August 7, 1962, and August 7, 1977. Transport/dispersion modeling will be needed to develop SIPs. Regional haze SIPs must provide an inventory of relevant emissions and describe plans for applying BART requirements.

Regional haze occurs because of light scatter and absorption. Most of the scattering from haze is due to Mie particle scattering from biogenic or anthropogenic aerosols in the micrometer size range. Rayleigh scattering from air molecules and very small particles (say, < 0.03 micrometers) also occurs. For example, the sky is blue because Raleigh scattering becomes progressively efficient at shorter wavelengths.

The small particles that commonly cause hazy conditions in the East are primarily composed of sulfate, nitrate, and "sea salts" in aqueous droplets during humid conditions; they also contain organic carbon compounds, elemental carbon (soot), and crustal material (*e.g.*, soil, dust, etc.).[2] Sulfate and nitrate pollutants contribute disproportionately to haze due to their high relative concentrations, and also strong chemical affinity for water. This hygroscopic tendency allows them to grow rapidly in the presence of significant water vapor (humidity), to an optimal particle size for scattering light (*i.e.*, 0.1 to 1 micrometer). Among the fine particulates that dominate light scattering are the ammonium sulfate compounds, $(NH_4)_2SO_4$ and $NH_4HSO_4$, which are formed by reactions of $H_2SO_4$, $SO_3$ and emitted $SO_2$ with ambient $NH_3$ and photochemical oxidants; and ammonium nitrate, $NH_4NO_3$, which is formed from $HNO_3$ via photochemical conversion of emitted $NO_x$. All of the highly soluble ammonium-based particles grow rapidly in size whenever the atmospheric relative humidity increases beyond, say, 75%.

According to a study of visibility in Phoenix, Arizona[3], (very fine) $PM_{2.5}$ ammonium sulfate particulate (secondary $PM_{2.5}$), transported as background air containing sulfates produced by smelters, coal-fired power plants, and cement and lime kilns emissions, is a minor contributor to light extinction in wintertime. But, it has increased impact on summertime visibility due to aerosol growth effects at higher humidity. Likewise, $PM_{2.5}$ ammonium nitrate particulate (secondary $PM_{2.5}$) preferentially occurs in significant quantities mainly in the winter, due to temperature and water vapor limitations. The nitrate particles originate from $NO_x$ emitted by motor vehicles, and ammonia from agricultural operations and a variety of other sources. This Phoenix visibility study concludes that ammonia emissions sources are poorly understood.[3]

## What Are the Sources of Ammonia?

The major sources of ammonia in the Mid-Atlantic States and New England, in order of importance, are emissions from livestock, fertilizer application, undisturbed soil, and natural fires.[4] Minor sources include industry, mobile sources, Publicly Owned Treatment Works (POTW) and humans, and various other sources.

Thus, accounting for ammonia sources in Virginia focuses primarily on (decomposed) animal wastes (excrement and urine). The process of calculating ammonia emissions is largely one of determining the amount of waste produced by animals in the Commonwealth, and then applying published emission factors[4] to the animal census data. Primarily this means farm animals — cattle and calves, hogs and pigs, sheep, and chickens and turkeys — but wild animals also contribute; e.g. some ammonia inventories include deer.

### Major Sources

**Livestock** waste is clearly the most important source of ammonia in our area of the country.[4] Existing inventories indicate cattle, swine, and poultry wastes are responsible for about 80% of national ammonia emissions, and Virginia has significant populations of these animals.

**Fertilizer application** is typically considered the second or third most important source of ammonia on a nationwide level, depending on whether the inventory includes soil emissions. Ammonia inventories usually estimate the contribution from fertilizer application as about 10% of the national total.

**Soil** is the most uncertain category of ammonia emissions, but may be one of the top two sources. Strader *et al.* at Carnegie Mellon University report that a 1990 inventory for the San Joaquin Valley in California estimated soil emissions to be 40% of the total. In general, high-quality emission factors for soil emissions do not exist, largely because the microbiology of nitrates, nitrites, and ammonium salts, and the rate of ammonia exchange are highly variable with soil composition, moisture and temperature, and are not well characterized or completely understood. Because of this uncertainty, many existing inventories simply do not include emissions from soil, but Strader *et al.* claim this omission is a "grievous error."

**Minor Sources**

**Industry (including new SCR and SNCR)** currently plays a relatively small role in ammonia emissions, only a few percent of the national total; see detailed Toxic Release Inventory (TRI) emissions for Virginia in Table 3 of this report.

One of the industrial sources, paradoxically, is pollution control equipment. As William Battye points out, ammonia emissions result from the use of ammonia or urea, with or without catalyst systems, to control $NO_x$ from fuel burning[4]. Substantial increases in SCR (selective catalytic reduction) and SNCR (selective non-catalytic reduction) installations are expected, and represent new sources for the present study. Note that, even with projections of substantial future increases in the number and size of SCR/SNCR installations, these sources may not become significantly large regional contributors. This is because $NH_3$ is an expensive commodity; slip concentrations tend to be relatively low; and finally, total $NH_3$ slip amounts are essentially linked to targeted $NO_x$ sources being reduced, which have well defined bounds (see later discussion of SCR and SNCR processes).

Battye lists **refrigeration** as a small (perhaps 5%) traditional source of ammonia emissions, which come from spills and leakage. Major spills are reported to the National Response Center, but the reports may be incomplete. Ammonia usage for refrigeration is minor compared to fertilizers and other uses, but ammonia refrigeration is expanding because of mandated chlorofluorocarbon cutbacks.

**Mobile sources** used to be minor contributors of ammonia, amounting to only a few percent of the national total. Also, there was considerable variability of ammonia emission data[5]. However very recent emission factors for ammonia (2001 data in Table 1) show a tenfold increase, from 1970-1980 emissions, with the implementation of catalyst controls for $NO_x$. Thus the present mobile source contribution in Virginia is about 17% of total ammonia emissions (see details in Table 1).

**Publically Owned Treatment Works (POTW) and Humans:** Ammonia emissions from POTW's, and human breath and perspiration, are also a small (perhaps 3%) portion of the national ammonia emission inventory. They can be estimated by using population figures from the census and emission factors from Battye *et al*. (1994).

**Other very minor sources** of ammonia in Virginia include domestic animals (cats and dogs), and wild animals. The burning of biomass may be minor, but should probably be considered uncertain until better data are available.

## Transport, Chemistry and Fate of Ammonia Emissions

Merely calculating the amount of ammonia produced is only part of defining any potential air pollution problem. The other is defining the distribution of its source strength, and subsequently calculating its contribution to air pollution processes.

The long range transport, photochemical conversion, and cloud microphysical processes by which locally released precursor pollutants, such as $SO_2$, $NO_x$, organic compounds, $NH_3$, and

many others form light-scattering (and light-absorbing) particles (and ozone) in the atmosphere, are complex. Gaseous intermediate chemical species adsorb and condense onto preexisting nuclei (e.g. metal oxides and salts), and form "quasi-equilibrated" gas, liquid and solid states. Generally, haze does not consist of discrete particles of sulfate, nitrate, or organic carbon. Rather, combinations of these gradually form, coagulate, and coalesce with existing particles moving through the atmosphere, absorb water vapor, and eventually grow large enough to scatter (and absorb) significant fractions of transmitted light.

A NESCAUM report notes that the role of atmospheric ammonia, i.e. specification of source strength, transport and atmospheric chemistry of ammonia / ammonium ion, needs further investigation. One complication is that recently implemented sulfate reductions tend to make more ammonium ion available for reaction with nitrate (and $NH_4HSO_4$), possibly resulting in less-than-anticipated visibility improvement, especially in wintertime.

Thus to determine the contribution of ammonia to regional haze, extensive transport and photochemical modeling will be required that includes all the complexities of tropospheric pollution, including acid rain deposition. An accurate ammonia inventory is only a first step.


**Further Details Regarding EPA Ammonia Emission Factors**

Fortunately, EPA has sponsored the calculation and assessment of previously calculated emission factors for ammonia. As a result, the most authoritative source of these data is R. Battye *et al.*, *Development and Selection of Ammonia Emission Factors* (August 1994)[4]. Battye, in turn, indicates that the most recent $NH_3$ inventory prepared in the U.S. is the Emissions Inventory for the National Particulate Matter Study, which used Bureau of Economic Activity data to grow the 1985 inventory of the National Acid Precipitation Assessment Program (NAPAP) to the 1990 study year.

The $NH_3$ emission factor data recommended by Battye et al., for use in future U.S. inventories, include: The European factors for agricultural sources (animal husbandry and fertilizer application); the *Compilation of Air Pollutant Emission Factors – Volume I* (*AP-42*) for most stationary industrial sources; and the NAPAP-derived factors for most combustion sources (including coal, oil, natural gas, mobile sources), and publicly owned treatment works (POTW's).

Battye also developed new emission factors for beet sugar production, froth flotation in mineral processing, mineral wool (fiberglass) production, refrigeration, **and** selective catalytic and noncatalytic reduction processes (SCR and SNCR) for control of nitrogen oxide ($NO_x$) emissions.

Discrete industrial sources of ammonia with no corresponding emission factors are identified through the Toxic Release Inventory for Virginia (see Battye, Executive Summary, p. ix 1994; also 1998 TRI data for Virginia, Table 3 of this report).

Battye subsequently updated selected portions of the 1994 ammonia emission factor report, e.g. on mobile sources and livestock, in March, 2000; and with V. Aneja, August, 2000[5]. See Tables 1 and 2 below. Further updates are forthcoming (personal communication, JC, 9/01)

Battye's August 1994 report notes, on page 2-11, that there is a mathematical error in the swine composite numbers (9.21 kg $NH_3$/animal-yr) presented by Asman (1992). Instead a value of 8.51 kg $NH_3$/animal-year was calculated directly from animal populations and emission factors presented by Asman (1992).

Finally, Robert Wooten, of the North Carolina Department of Environment and Natural Resources, told us (JC) the Battye numbers were developed based on European animal husbandry practices, which differ somewhat from American ones (personal communication, April, 2001). He also cited an apparent error in the numbers for swine in the Battye report; the swine number is overstated, Mr. Wooten says, by 40-50%.

**Detailed Checks on Livestock Sources in Virginia**

The Battye emission factors must be applied to the numbers of *live* animals in Virginia. The emission of ammonia from waste produced by farm animals may thus be calculated from data tabulated by the U.S. Department of Agriculture for each state. Information on crops, livestock, poultry, and county summaries for Virginia are available at the web address, *http://www.nass.usda.gov/va/rlsetoc.htm*. For example, county estimates for all cattle, including beef cows and milk cows, are given at *http://www.nass.usda.gov/va/pg068&69.htm*. As of January 1, 1998, the estimated state total for all cattle was 1,760,000 head.

An updated inventory of Virginia animals was obtained (by JMH, May 15, 2001) from Dr. Wayne Purcell at VPI and SU (phone, 540-231-7725; e-mail, PURCELL@vt.edu) as follows:

| **Animal Category** | **Data Date** | **Live Animals** |
|---|---|---|
| Cattle & Calves | (1/00) | 1,600,000 |
| Milk Cows | (1/00) | 119,000 |
| Hogs and pigs | (12/99) | 370,000 |
| Turkeys | (12/99) | 24,000,000 |
| Chickens (except broilers) | (12/99) | 4,641,000 |
| Broilers | (12/99) | 268,700 |
| Sheep & Lambs | (1/00) | 61,000 |
| Horses (includes mules) | (1998) | 150,000 |

By adopting Ammonia Emission Factors from Table 2-2 of the 1994 Battye EPA report[4], and assigning animal counts derived from Purcell's Animal Inventory (above), a total annual $NH_3$ air emission contribution from animals in Virginia of **64,534,000 lb $NH_3$/yr** was estimated. Components of this calculation are shown in the first three columns of Table 4, in the present report. As a quasi-independent check, an alternate air emission total of **91,556,000 lbs $NH_3$/yr** was also calculated in Table 4 (last three columns), by averaging the first six columns of recently-estimated ammonia emission factors shown in Table 2.

Both of the above estimated ammonia air emissions from animals in Virginia can be compared with the 1998 Toxic Release Inventory (TRI), Total Air Emissions of ammonia in Virginia (Table 3) of **8,114,000 lb $NH_3$/yr** from the 69 TRI emitters in Virginia. [Note in Table 3 that additional On-site releases to water and soil (= 95,231 = 8,209,540 – 8,114,309) and similar "Off-site Releases" (165,151) represent only 3% of the "Total of All Releases."] After adding respective animal totals to the Total TRI Air Emissions, Table 4 shows the emission projections for animals amount to **88.8%** and **91.9%** of all $NH_3$ emissions from animals plus all

1998 TRI sources.  Clearly, the ammonia emissions from animals alone, neglecting contributions from fertilization and other sources, has overwhelmed industrial contributions by a factor of ten.


**Characteristics of SCR, SNCR Processes**


In SCR systems, $NH_3$ is injected into the combustion flue gas, which is then passed through a catalyst bed.  The $NH_3$ reacts 1:1 with NO (and $O_2$) to produce $N_2$ and $H_2O$.  $NO_2$ reacts similarly.  The catalyst enables this chemical reduction to proceed rapidly at typical flue gas temperatures.  The amount of $NH_3$ slip increases, relative to the NO input, when the catalyst becomes degraded or the catalyst bed temperature is not optimum.  In the (non-catalytic) SNCR process, $NH_3$ (or urea) must be injected into the flue gas at higher temperatures, and the conversion becomes significantly less efficient.

Battye cites target $NH_3$ slip emission concentrations of about 5 to 10 ppm for SCR systems, and 20 to 30 ppm for SNCR systems (*Chemical Economics Handbook*, SRI International, Palo Alto, California, 1989).  However, detailed data summarized in the Battye *et al*. report (Table 5-4)[4] showed that "$NH_3$ slip is extremely variable."   Thus Battye et al. adopted "For the purposes of emission factor development, an average $NH_3$ slip of 15 ppm for SCR systems, and 30 ppm for SNCR systems.  These values represent a synthesis of manufacturers' information and the data in Table 5-4."  Note that superior performance is often claimed for more recent (or proposed) SCR installations *if* the catalyst bed is used optimally and not degraded.

Given appropriate estimates of *time-averaged* $NH_3$ slips, the problem of estimating future cumulative $NH_3$ <u>mass</u> emissions (for comparison with the animal emissions) requires detailed information on projected system installations and operational flows, which may be difficult to obtain and tedious to analyze.

A much simpler method for estimating the overall impact of $NH_3$ slip emissions stems from fundamental process information provided by Battye *et al*[4] (which, similarly, may require updating due to process improvements).  For a typical SNCR process, the use of a 1:1 $NH_3$/NO molar input ratio produces *less than* a 40% reduction of NO to $N_2$ and $H_2O$; whereas a 2:1 ratio produces *up to* a 60% reduction.  By definition, these translate to relative $NH_3$ slips of approximately 0.6:1 and 1.4:1 mole $NH_3$-slip/initial-mole NO, respectively.  However, for a typical SCR process, a 1:1 ratio produces an 80% reduction of NO, which translates to a relative $NH_3$ slip no larger than 0.2:1.  Thus, when proposed amounts of NO targeted for reduction are defined for respective processes, the above molar ratios may be used to project expected $NH_3$ slip emissions relative to NO.  For example, the **reduction of 1000 lbs of NO** would produce **1324 lb $NH_3$ slip for a SNCR** process operating at 60% efficiency, and **142 lb $NH_3$ slip for a SCR** process operating at 80% efficiency.  These numbers are used in the following section.


**Proposed SCR, SNCR Sources in Virginia**


A provisional accounting of proposed SCR and SNCR sources indicates the following (personal communication from Robert Asplund, Dominion Generation, 9/01).  Dominion Generation acquired three stoker-fired power plants previously owned by Louisville Gas and Electric (LG&E).  These include respective plants at Hopewell and Altivista (coal and wood)

that have SNCR systems; and a Southhampton plant that burns coal and tall oil, but has neither SCR nor SNCR systems.

Dominion Generation is installing SCR's on three coal-fired units at their Chesterfield plant. These should become operational in 2004 or 2005. The smallest (fourth) unit will operate without an SCR system. Dominion Generation will also be operating the Belle Meede plant, in Richmond, with a SCR system. Finally, there will also be a number of SCR systems operating in West Virginia.

Current projections, by Dominion Generation, indicate that out of 420,000,000 lbs $NO_x$ emitted in Virginia during the 5-month ozone season (May through September), 61,000,000 lbs $NO_x$ (as NO) are targeted for reduction over CY's 2004-2007 (Telecon from Andy Gates and Lenny Dupuis, facilitated by Robert Asplund, Dominion Generation, 9/27/01). This projection also included an estimate that 80 to 90% of the NO reduction would be accomplished using SCR. We will assume an average of 85% SCR, although 90% or higher would be more favorable.

If we partition $NH_3$ slip emission amounts for the respective SCR (85% of the $NO_x$) and SNCR (15%) processes, and use respective slip ratios estimated in the previous section, we obtain a weighted mean of **319 lb $NH_3$ slip emissions per 1000 lb $NO_x$** reduced. For the provisional targeted reduction of 61,000,000 lbs $NO_x$ during the 5-month ozone season, this translates to a weighted-average annual $NH_3$ slip emission of **19,500,000 lb $NH_3$**. This projected amount is 240% of the total 1998 TRI emissions in Table 3, and 25% of the averaged annual emissions from animals in Table 4, which are 78,000,000 lb $NH_3$.

Finally, however, *if* proposed SCR installations are substantially more efficient and only release **100 lb $NH_3$ slip emissions per 1000 lb $NO_x$** reduced, this would translate to a weighted-average annual $NH_3$ slip emission of **6,100,000 lb $NH_3$**. This projected amount would have greatly reduced impact, being only 75% the total 1998 TRI emissions in Table 3, and about 7.8% of the average annual emissions from animals in Table 4. Altogether, this idealized projection of $NH_3$ slip emissions from assumed high-efficiency SCR installations in Virginia (6.1 Mlb) would be **only 4.4% of total $NH_3$ air emissions** by animals (78 Mlb), fertilization (say, 9 Mlb), TRI-listed and SCR sources (14 Mlb) in Virginia, and our estimate of other contributions from refrigeration, mobile sources, POTW's, etc (37 Mlb).

**Summary and Conclusions**

The original objective of this study was to determine methodology for conducting an ammonia ($NH_3$) air-emission inventory. Although detailed assessments of ammonia ($NH_3$) slip emission concentrations and quantities, for projected installations of SCR's and SNCR's in Virginia, were clearly beyond the scope of our study, an approximate regional assessment of $NH_3$ air emissions <u>was</u> developed.

Projected $NH_3$ slip quantities, for planned SCR and SNCR installations in Virginia (Dominion Generation, for 2004-2007), were defined based on targeted $NO_x$ reductions during "the 5-month ozone season." These projected total $NH_3$ slip quantities for a 5-month season were relatively small (from 12.8% to 4.4%), compared to estimated total annual $NH_3$ air emissions in Virginia from animal waste, fertilization, soil, TRI-listed and SCR/SNCR sources, refrigeration, mobile sources (which have grown considerably with recent catalytic mufflers), and Publicly Owned Treatment Works.

The first estimate (12.8%) corresponds to DG's projection of 85% SCR and 15% SNCR process contributions. It used average $NH_3$ slip efficiencies recommended by Battye *et al.*[4],

based on extensive but highly variable data obtained a decade ago. The lower impact estimate of 4.4% applies *if* highly efficient and well-maintained SCR processes are utilized for nearly all $NO_x$ reduction, so that utilization of much less efficient SNCR processes is effectively eliminated.

Thus our analyses suggest that (preferable) SCR process installations would not become significant regional contributors of $NH_3$ air emissions. Important operational factors that favor relatively low local and regional impacts are: $NH_3$ is moderately expensive, so that operating costs of $NH_3$ wastage weigh significantly against the costs of proper catalyst bed maintenance; $NH_3$ slip concentrations from modern SCR's, which may be subject to regulation, are expected to be relatively low (say, 5 ppm on average); and finally, total $NH_3$ amounts (consumed plus slip) are essentially linked to target $NO_x$ sources being "reduced," which have well defined bounds.

It is concluded, based on the Battye *et al*. studies[4,5] and the present assessment, that (1) efforts to develop and maintain a detailed ammonia inventory appear unnecessary, and (2) incremental regional (and local) effects of expected additional $NH_3$ slip emissions, from the (assumed) predominance of SCR applications, should be relatively small for the next decade.

**Table 1**

**Mobile Source NH₃ Emissions**

Comparison of recent tests to emission inventory factors

(DEQ-estimated Vehicle Miles of Travel in VA = 213,035,000 miles/day, for 2001)

| Source | NH₃ emission factor (mg/km) | Location, year, comments |
|---|---|---|
| **Recent tests** | | |
| Fraser & Cass, 1998 | 72 | Van Nuys tunnel, 1993 |
| Kean, *et al.*, 2000 | 49 | Caldicott tunnel, CA, 1999 |
| Baum, *et al.*, 2000 | na | Remote tailpipe sensing, average $NH_3$-to-$NO_x$ ratio ranged from 0-10, averaging 0.67, twice that in Kean |
| **Very Recent Multicomponent Remote Sensing; in California (considered most reliable)** | | |
| Baum, et al., Env. Sci. Tech., 2001, **35**, pp. 3735-3741 | 94 ± 8 | First direct remote sensing measurement of $NH_3$; 2091 Light Duty Motor Vehicles @ 45-55 mph |
| **Previous Inventory Factors** | | |
| EPA NET | 85 | |
| California | 16 | |

Source: Battye (2000 & 2001)

# Table 2

## Recent Published Emission Factors for Livestock
### (kg-NH$_3$/animal-year)

| Source | EPA 1994 report | ECETOC (1994) | EMEP (1996) | Bouwman (1997) | UNECE (Van Der Hoek) (1998) | Missel-brook (2000) | Others | Estimate from MWPS |
|---|---|---|---|---|---|---|---|---|
| Dairy Cow | 39.7 | 39.5 | 29.1 | 24.8 | 28.5 | 26.5 | 23[a] | 11 - 40 |
| Beef Cow | 23.1 | 27.8 | 14.6 | 9.5 | 14.3 | 6.8 | | 9 - 19 |
| Swine | 9.2 | 4.25 | - | 4.9 | - | - | | |
| Sows | 16 | - | 16.6 | - | 16.4 | 5.2 | | 14 - 17 |
| | | | | | | | 5.9 - 12[b] | |
| Pigs | 7 | - | 6.46 | - | 6.4 | 4.8 | | 5 - 10 |
| Lagoons only | | | | | | | 2.2[c] 2.3[d] | |
| Poultry | 0.24 | 0.19 | - | 0.24 | 0.37 | - | | |
| Layers | - | - | 0.38 | - | - | 0.45 | | 0.2 - 0.4 |
| Broilers | - | - | 0.27 | - | 0.28 | 0.23 | | 0.1 - 0.2 |
| Sheep | 1.7 | 1.8 | 1.46 | 0.77 | 1.34 | 0.73 | | |
| Horses | 12.1 | 11.9 | - | 9.2 | 8.0 | - | | |

[a] McCulloch et al. (1998), summer only for finishing pigs
[b] Schmidt and Winegar (1996)
[c] Aneja (2000)
[d] Harper (2000)

Source: Battye (2000)

**Table 3.** 1998 Toxic Release Inventory (TRI) Data – Ammonia Air Emission Releases in Virginia.  Source:  EPA TRI Database

| Row # | Facility | City | Total Air Emissions (lbs) | Total On-site Releases (lbs) | Total Off-site Releases (lbs) | Total of All Releases (lbs) |
|---|---|---|---|---|---|---|
| 1 | ALLIED SIGNAL INC. HOPEWELL PLANT | HOPEWELL | 4827700 | 4874000 | 0 | 4874000 |
| 2 | AMERICAN SAFETY RAZOR INC. | VERONA | 1054 | 1054 | 0 | 1054 |
| 3 | AMOCO PETROLEUM PRODS. YORKTOWN REFY. | GRAFTON | 0 | 1900 | 0 | 1900 |
| 4 | AMSCO PRODUCTS-TFS AUTOMOTIVE. | WYTHEVILLE | 2 | 2 | 0 | 2 |
| 5 | ANHEUSER-BUSCH INC. | WILLIAMSBURG | 4724 | 4724 | 0 | 4724 |
| 6 | AUSTIN POWDER CO. | WISE | 0 | 9 | 0 | 9 |
| 7 | AUTOMATA INTL. | STERLING | 23600 | 23600 | 0 | 23600 |
| 8 | B.I. CHEMICALS INC. | PETERSBURG | 79250 | 79250 | 0 | 79250 |
| 9 | BELLEMEADE POWER STATION | RICHMOND | . | . | . | . |
| 10 | BIRCHWOOD POWER FACILITY | SEALSTON | 133 | 133 | 0 | 133 |
| 11 | BOAR'S HEAD PROVISIONS CO. INC. | JARRATT | 24000 | 24000 | 0 | 24000 |
| 12 | BORDEN CHEMICAL INC. | WAVERLY | 449 | 449 | 0 | 449 |
| 13 | BROWN & WILLIAMSON TOBACCO CORP. | CHESTER | 12500 | 12730 | 2407 | 15137 |
| 14 | CARTER-WALLACE INC. | COLONIAL HEIGHTS | 464431 | 464431 | 0 | 464431 |
| 15 | CELANESE CHEMICAL DIV. | PORTSMOUTH | 4976 | 4976 | 0 | 4976 |
| 16 | CHEMSOLV INC. | ROANOKE | . | . | . | . |
| 17 | CLARKSVILLE FINISHING PLANT | CLARKSVILLE | 1090 | 3046 | 12568 | 15614 |
| 18 | CONAGRA FROZEN FOODS | CROZET | 38000 | 38000 | 0 | 38000 |
| 19 | DEGESCH AMERICA,INC | WEYERS CAVE | 5322 | 5322 | 0 | 5322 |
| 20 | DOSWELL COMBINED CYCLE FACILITY | ASHLAND | 57000 | 57000 | 0 | 57000 |
| 21 | EMERSON ELECTRIC CO.  ALCO CONTROLS DIV. | WYTHEVILLE | . | . | . | . |
| 22 | FEDERAL-MOGUL CORP. | BLACKSBURG | . | . | . | . |
| 23 | GE CO., FANUC AUTOMATION N.A. INC. | CHARLOTTESVILLE | 2570 | 2570 | 0 | 2570 |
| 24 | GEORGIA-PACIFIC CORP. BROOKNEAL OSB | GLADYS | 53382 | 53382 | 0 | 53382 |
| 25 | GILMER INDS. INC. | HARRISONBURG | . | . | . | . |
| 26 | GORDONSVILLE ENERGY L.P. | GORDONSVILLE | 608 | 858 | 0 | 858 |
| 27 | GREIF BROS. CORP. OF VIRGINIA | RIVERVILLE | 0 | 24263 | 0 | 24263 |
| 28 | GWALTNEY OF SMITHFIELD LTD. | SMITHFIELD | 12763 | 12763 | 0 | 12763 |
| 29 | HERCULES INC. | HOPEWELL | 390 | 390 | 0 | 390 |
| 30 | HOLLY FARMS/TYSON FOODS INC. | GLEN ALLEN | 34140 | 34140 | 0 | 34140 |
| 31 | HOLLY FARMS/TYSON FOODS INC. | TEMPERANCEVILLE | 13154 | 13154 | 0 | 13154 |
| 32 | LEBANON CHEMICAL CORP. | SEALSTON | . | . | . | . |
| 33 | LEBANON CHEMICAL CORP. | WEST POINT | 171 | 171 | 0 | 171 |
| 34 | LEBANON CHEMICAL CORP. | CHESAPEAKE | . | . | . | . |
| 35 | LG&E-WESTMORELAND ALTAVISTA COGENERATION FACILITY | ALTAVISTA | 11005 | 11005 | 0 | 11005 |
| 36 | LG&E-WESTMORELAND HOPEWELL | HOPEWELL | 12005 | 12005 | 0 | 12005 |

| Row # | Facility | City | Total Air Emissions (lbs) | Total On-site Releases (lbs) | Total Off-site Releases (lbs) | Total of All Releases (lbs) |
|---|---|---|---|---|---|---|
| | COGENERATION FACILITY | | | | | |
| 37 | MASONITE CORP. | DANVILLE | 0 | 0 | 0 | 0 |
| 38 | MERCK & CO. INC. | ELKTON | 6600 | 7250 | 0 | 7250 |
| 39 | NABISCO BISCUIT CO. 130A DIV. OF NABISCO INC. 130 | RICHMOND | 87325 | 87325 | 0 | 87325 |
| 40 | NEWPORT NEWS SHIPBUILDING | NEWPORT NEWS | 8900 | 8900 | 147900 | 156800 |
| 41 | OMEGA PROTEIN INC. | REEDVILLE | 33000 | 33000 | 0 | 33000 |
| 42 | OWENS-BROCKWAY GLASS CONTAINER INC. | TOANO | 7300 | 7300 | 0 | 7300 |
| 43 | OWENS-BROCKWAY GLASS CONTAINER INC. | RINGGOLD | 5100 | 5100 | 0 | 5100 |
| 44 | PERDUE FARMS INC. ACCOMAC PROCESSING PLANT | ACCOMAC | 24000 | 24050 | 0 | 24050 |
| 45 | PHILIP MORRIS USA BL/LPF/TQAF PLANT | RICHMOND | 1400260 | 1400260 | 1700 | 1401960 |
| 46 | PHILIP MORRIS USA MFG. CENTER | RICHMOND | 30005 | 30005 | 26 | 30031 |
| 47 | PHILIP MORRIS USA PARK 500 SITE | CHESTER | 36260 | 36620 | 550 | 37170 |
| 48 | PRAXAIR INC. | HOPEWELL | 11220 | 11220 | 0 | 11220 |
| 49 | PRILLAMAN CHEMICAL CORP. | SUFFOLK | . | . | . | . |
| 50 | REXNORD CORP. | STUARTS DRAFT | 28403 | 28403 | 0 | 28403 |
| 51 | RICH PRODS. CORP. | WINCHESTER | 9196 | 9196 | 0 | 9196 |
| 52 | ROYSTER-CLARK INC. | CHESAPEAKE | 9674 | 12474 | 0 | 12474 |
| 53 | SCHRADER-BRIDGEPORT INTL. INC. | ALTAVISTA | 19630 | 19630 | 0 | 19630 |
| 54 | SEWELL PRODS. INC. | SALEM | 50 | 50 | 0 | 50 |
| 55 | SMITHFIELD PACKING CO. INC. - SMITHFIELD VIRGINIA | SMITHFIELD | 8177 | 8177 | 0 | 8177 |
| 56 | SOUTHEASTERN ADHESIVES CO. | RIDGEWAY | 994 | 1094 | 0 | 1094 |
| 57 | SOUTHERN STATES CO-OP. INC. | CHESAPEAKE | 15127 | 15127 | 0 | 15127 |
| 58 | ST. LAURENT PAPER PRODS. CORP. | WEST POINT | 147126 | 148687 | 0 | 148687 |
| 59 | STONE CONTAINER CORP. | HOPEWELL | 110000 | 110000 | 0 | 110000 |
| 60 | U.S. ARMY RADFORD ARMY AMMUNITION PLANT | RADFORD | 24017 | 28217 | 0 | 28217 |
| 61 | UNION CAMP CORP. FINE PAPER | FRANKLIN | 150120 | 157520 | 0 | 157520 |
| 62 | VIASYSTEMS TECHS.L.L.C | RICHMOND | 1234 | 1234 | 0 | 1234 |
| 63 | WAKO CHEMICALS  USA INC. | RICHMOND | 1000 | 1000 | 0 | 1000 |
| 64 | WAMPLER FOODS INC. | STANLEY | 0 | 0 | 0 | 0 |
| 65 | WAMPLER FOODS INC. | TIMBERVILLE | 0 | 0 | 0 | 0 |
| 66 | WAMPLER FOODS INC. HINTON PROCESSING PLANT | HINTON | 0 | 0 | 0 | 0 |
| 67 | WAYTEC ELECTRONICS CORP. | LYNCHBURG | 9232 | 9234 | 0 | 9234 |
| 68 | WESTVACO CORP. BLEACHED BOARD DIV. | COVINGTON | 240260 | 243460 | 0 | 243460 |
| 69 | WESTVACO CORPORATION/CHEMICAL DIV. | COVINGTON | 5680 | 5680 | 0 | 5680 |
| | **Total lbs** | | **8,114,309** | **8,209,540** | **165,151** | **8,374,691** |

## Table 4 (Modified Table 2)

### Application of Recent 1985 NAPAP, and Table 2 (CY 2000, above) Emission Factors for Livestock

| Source | Yr 1985 NAPAP Table 2-2 <br><br> kg-NH$_3$/ animal-yr | Virginia Animal Inventory <br><br> (generally 1999-2000) | Metric Tons Ammonia per year | Yr 2000 (average of first six factors in Table 2) <br><br> kg-NH$_3$/ animal-yr | Virginia Animal Inventory <br><br> (generally 1999-2000) | Metric Tons Ammonia per year |
|---|---|---|---|---|---|---|
| Dairy Cow | | | | 31.35 | 119,000 | 3,731 |
|   Confined | 12.25 | | | | | |
|   Ranging | 20.41 | | | | | |
|   Average | 16.33 | 119,000 | 1,943 | | | |
| | | | | | | |
| Beef Cow | | | | 16.02 | 1,600,000 | 25,632 |
|   Feedlots | 5.90 | | | | | |
|   Ranging | 20.14 | | | | | |
|   Average | 13.02 | 1,600,000 | 20,832 | | | |
| | | | | | | |
| Swine | | | | | | |
|   Sows | | | | 13.55 | | |
| | | | | | | |
| Pigs | | | | 6.17 | 370,000 | 2,283 |
|   Ranging | 17.69 | | | | | |
|   Confined | 1.95 | 370,000 | 722 | | | |
| | | | | | | |
| Poultry | | | | | | |
|   Layers | 0.15 | 4,641,000 | 696 | 0.42 | 4,641,000 | 1,949 |
|   Broilers | 0.02 | 268,700 | 5 | 0.26 | 268,700 | 70 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Turkeys | 0.13 | 24,000,000 | 3,120 | 0.26 | 24,000,000 | 6,240 |
| Sheep Ranging | 2.04 | 61,000 | 124 | 1.30 | 61,000 | 79 |
| Horses | 12.20 | 150,000 | 1,830 | 10.30 | 150,000 | 1,545 |
| Total NH$_3$ /yr Metric Tons | | | 29,272 | | | 41,529 |
| lbs | | | 64,534,000 | | | 91,556,000 |
| **Animal NH$_3$**, as Percent of Animal + all 69 TRI in Table 3 | | | **88.8%** | | | **91.9%** |

[1] Presentation by Jeffrey A. Panek, "Regional Haze Regulations and Class I Area Air Quality Related Values," Industry Environmental Council, Chicago, Illinois, March 14, 2000.

[2] Northeast States for Coordinated Air Use Management, Regional Haze and Visibility in the Northeast and Mid-Atlantic States, prepared for the Ozone Transport Commission, *http://www.nescaum.org/committees/haze.html*.

[3] Phoenix Feasibility Study at 5.

[4] R. Starder et al., Development of an Ammonia Emissions Inventory for the Mid-Atlantic States and New England (October 18, 2000).

[5] W. Battye, "Air Emissions of Ammonia: Sources, Estimation Methods, and Uncertainties, Presentation at Shared Resource Workshop – Airsheds and Watersheds: Significance of Ammonia to Coastal and Estuarian Areas, November 15, 2000.